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A MODEL OF THE ION WAKE OF MARS

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Abstract. Observations from the PHOBOS spacecraft suggest that, for the most part, the Martian magnetotail is induced instead of intrinsic. In this paper, test particle techniques are used to determine how the associated ion wake might appear to detectors behind Mars if it is produced primarily by planetary ions picked up by the solar wind in the dayside exosphere. The results suggest that low energy (< 10 keV) pickup ions populate the inner wake, while a more energetic component is present in the outer magnetosheath and adjacent solar wind. The latter has a finite gyroradius related spatial asymmetry controlled by the interplanetary field orientation. This asymmetry is analogous to, but stronger than, that which appears in Venus ion wake observations because of the smaller obstacle size and weaker interplanetary field at Mars.

Introduction

It has long been recognized [e.g., Michel, 1971] that at the weakly magnetized planets, Venus and Mars, the planetary exospheres can extend into the magnetosheath and solar wind because the effective "obstacles" to the latter are little more than planet-size. It is also known that both terrestrial planets have extensive hot atomic oxygen coronae produced by the dissociative recombination of the O_2^+ in their ionospheres [cf. McElroy, 1972, Nagy and Cravens, 1988, Ip, 1988]. These heavy neutrals are ionized by photoionization, impact ionization, or charge-exchange in the flowing plasma, and then "picked up" in the flow in a manner reminiscent of that in cometary environments. However, because the obstacle cross section at these planets is less than or comparable to the O^+ "pickup ion" gyroradii, some particles re-impact the deep dayside atmosphere [cf. Cloutier et al., 1974]. This asymmetrical loss, together with the cycloidal geometry of the trajectories resulting from acceleration by the convection electric field $E = -V \times B$ (where V is the background plasma velocity and B the convected magnetic field), gives the pickup ion population around the planet a hemispheric asymmetry that is controlled by the interplanetary magnetic field orientation [e.g., see Phillips et al., 1987]. The result downstream of the planet is an asymmetric planetary ion "wake." The presence of a spatial asymmetry that is organized by the interplanetary field orientation has already been established for pickup ions detected in the wake of Venus [cf. Slavin et al., 1989, Intriligator, 1989]. The Martian ion wake has only recently been observed on PHOBOS 2 (cf. papers by Lundin et al., this issue), and so the details of its morphology are still subject to investigation. Also recently, Luhmann and Schwingenschuh [1989] described a model for the energetic pickup ions around Mars analogous to that used to explain certain features observed at Venus [cf. Phillips et al., 1987]. This model shows how much more pronounced the ion asymmetries at Mars may be because of the combination of the smaller size of the Martian obstacle (e.g., Mars' radius is $R_M \approx 3394$ km as opposed to Venus' $R_V \approx 6053$ km) and the weaker interplanetary magnetic field at 1.5 AU (~3 nT as opposed to ~10 nT). However, these authors considered only the pickup ion population in the Martian magnetosheath and surrounding solar wind. Since the PHOBOS 2 observations of planetary ions were obtained mainly in the central wake or tail region, it is timely to consider the fate of those particles which pass through the inner boundary of the Martian magnetosheath but escape absorption by the atmosphere.

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Description of the Model

The present model is an extension of that used by Luhmann and Schwingenschuh [1989]. In their analysis, as in the analysis described here, singly ionized atomic oxygen test particles were launched into background electric and magnetic fields described by Spreiter and Stahara's [1980] gas dynamic model of a planetary magnetosheath. The starting point grid for the particles consisted of 31 hemispherical shells separated by $\Delta \log r = .05$ planetary radii nested over the dayside of the planet, each containing 500 randomly scattered starting points. The particles were given initial energies of only 10 eV (a typical photoion energy), so that they were effectively at rest. After their trajectories were numerically calculated, they were weighted in accord with the exosphere model of Nagy and Cravens [1988] to obtain fluxes and energy spectra. No scattering or other interactions altered these trajectories. However, in the earlier work, the significant numbers of test particles that impacted the gas dynamic model obstacle were excluded from the calculation after impact because the field and flow model inside the obstacle was undefined. As a result of the PHOBOS 2 mission, it is now known that the Martian magnetotail is primarily induced [Schwingenschuh et al., 1989], or made up of draped interplanetary flux tubes that have become mass-loaded and sink into the wake as at Venus [cf. review by Russell, 1986].

In the absence of a global simulation of the solar wind interaction including the wake structure, one can construct a rough but potentially useful induced tail model by tailoring a model of a comet tail (which is similarly produced by mass-loading [e.g., see McComas et al., 1987]) to fit inside the obstacle of the gas dynamic magnetosheath model. A comet model that is well-suited to this purpose is the fairly simple version developed by Wallis and Johnstone [1983] for tracing particles in a cometary environment. This model is based on the assumption that one has a monodirectional flow field which, by virtue of mass-loading, has a localized stagnation region around the flow axis. With such an assumption, and the assumption of a transverse magnetic field in the unperturbed flow, they obtained analytical expressions which describe both the flow and the frozen-in field for a particular spatial profile of the stagnating flow. While this model does not take MHD effects into account, the consistent relationship between the flow and field allows one to approximately evaluate the Lorentz force in the wakes of planets with induced magnetotails.

The present model uses a gas dynamic magnetosheath model for a Mach number 4.5 solar wind and an obstacle shape described by the "shape factor" H/R_0 = .25 [see Spreiter and Stahara, 1980]. Care was taken to adjust the Wallis and Johnstone model parameters to ensure a fairly smooth transition in velocity and magnetic field strength across the inner boundary of the post-terminator magnetosheath. The interplanetary magnetic field was assumed to be constant at 4 nT in the +y direction, where x, y and z are Mars-centered cartesian coordinates with x pointing toward the sun and z pointing north from the Martian orbit plane. Figure 1 shows some magnetic field lines for the combined model, and Figure 2 shows how this magnetic field would appear on a spacecraft in a circular orbit near that of the moon Phobos. The simulated time series in Figure 2 resembles the observations presented by Schwingenschuh et al. [1989] which show a smooth transition between the field of the magnetosheath and that of the tail. It is also notable that the appearance of the tail model is similar to that obtained statistically for Venus by McComas et al. [1987].

Test particles which pass through the magnetosheath model boundary immediately find themselves under the influence of the fields in the comet tail model. However, if they pass within 1.1

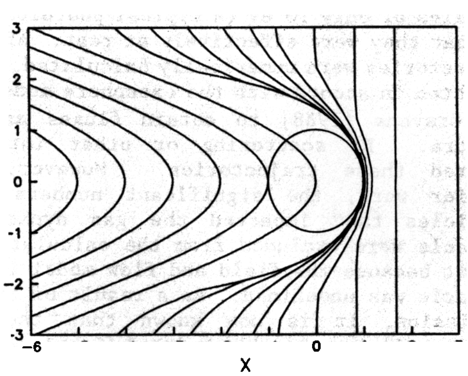

Fig. 1. Some field lines of the magnetosheath and comet tail models are superposed to illustrate how the magnetic field geometry appears to test particles in the combined model used here. The units are planetary radii. A dashed line marks the bow shock location. These field lines are drawn in the plane containing the interplanetary magnetic field which passes through the subsolar point (e.g., the "equatorial" plane). The tail field always lies in planes parallel to this plane since in the comet model used there is no diversion of the antisolar flow.

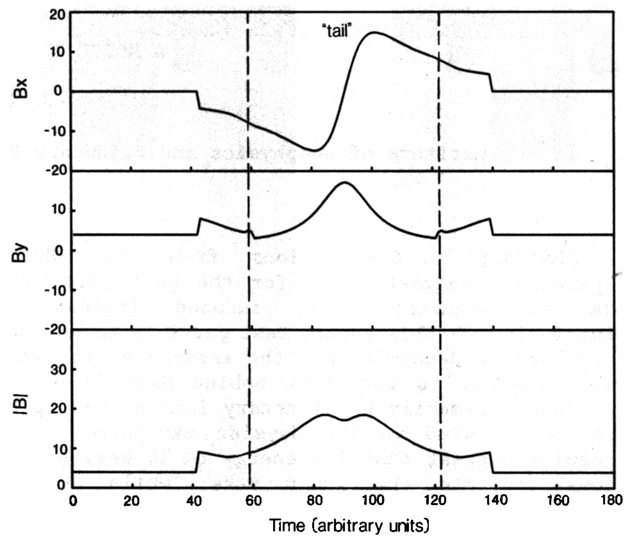

Fig. 2. Modelled "time series" of two magnetic field components and the total field as it might be observed from a spacecraft orbiting Mars near the orbit of the moon Phobos. The boundary of the "tail" model is identified by the dashed lines. The bow shock is identifiable by the sudden jumps (inbound and outbound) in field magnitude.

planetary radii of the planet surface, they are considered "reabsorbed" and dropped from further calculations. Most of the particles that impact the obstacle sunward of the terminator fall into this latter category. The trajectories of a few test particles are reproduced in Figure 3. These illustrate that there are wake ion populations which occupy the "tail" region, the magnetosheath, and the nearby solar wind. The latter are located further from the tail axis in the direction of the interplanetary electric field.

Results

Figure 4 displays the results as "contours" of the logarithm of the omnidirectional number flux at different energies for selected positions (in x) down the tail superposed on circles representing the optical shadow, obstacle and shock boundaries.

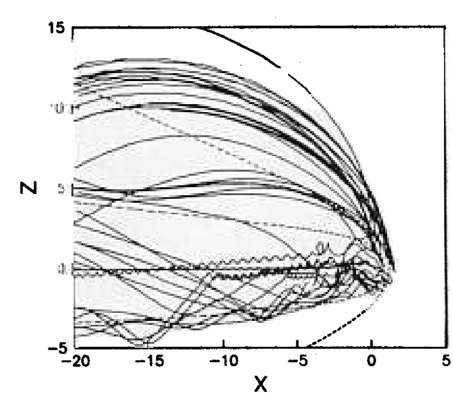

Fig. 3. Sample O^+ pickup ion trajectories projected in the noon-midnight plane. The interplanetary field is in the +y direction. The locations of the bow shock and magnetosheath (obstacle) boundaries are identified by the dashed curves.

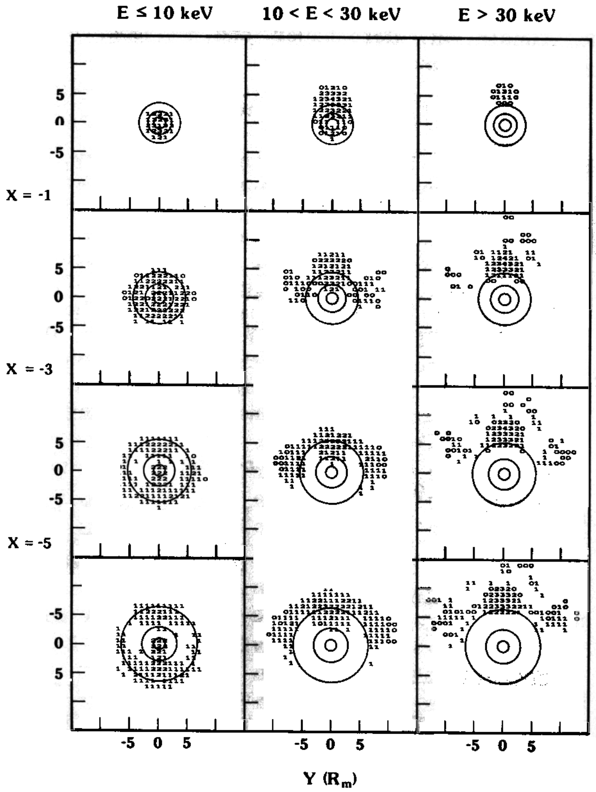

Fig. 4. "Contours" of omnidirectional number flux at various distances (x) down the ion wake. The numbers denote the (rounded-off) log of the flux. The concentric circles show the approximate locations of the optical shadow, the magnetosheath "obstacle" boundary, and the bow shock. These cross sections show that the "tail" population is a lower energy population than the sheath and solar wind population; and that they are spatially separated. The asymmetry due to the finite gyroradius of the picked up ions is visible only in the higher energy sheath and solar wind populations.

These plots suggest that there are basically two components of the pickup ion population in the vicinity of Mars. One of these, the "sheath and solar wind" population, is that discussed by Luhmann and Schwingenschuh [1989]. The particles in this more energetic population are essentially those that have been accelerated in the magnetosheath and solar wind (where they can attain maximum energies equivalent to twice the solar wind velocity) but never interact with the wake or tail field. When the interplanetary magnetic field is in the +y direction, these are generally made up of those ions which have been launched in the northern part of the exosphere although some of the lower energy members of this population leak around from the south. The other component, the "tail" population, consists of those pickup ions launched in the flanks and in the south polar exosphere which escape impact on the planetary lower atmosphere and so enter the wake just behind the planet. This component is less energetic because the ions gain significant energy only while they are upstream. Once they enter the wake, they are in a region where the magnetic field and flow are, on the average, more nearly parallel, and hence add little additional acceleration. In Figure 5

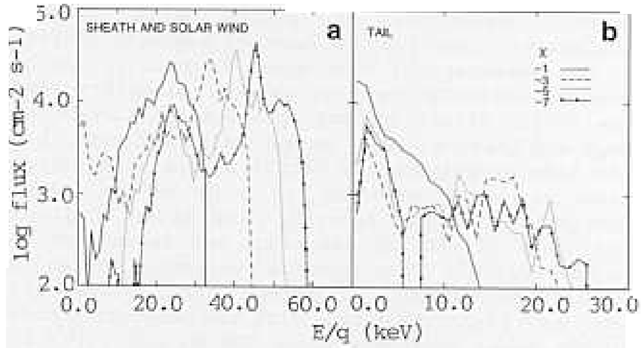

Fig. 5. Omnidirectional flux energy spectra are shown for a) the "tail" population and b) the sheath and solar wind population at several positions (x) downstream.

the omnidirectional energy spectra which appear in the tail within 3 R_M of the tail axis are contrasted with the spectra for the rest of the particles, which are essentially the same as examples shown by Luhmann and Schwingenschuh [1989].

Discussion

One must consider several properties of the model carefully when comparing it with spacecraft data. For example, because the flow is fastest upstream of the bow shock, the particles with the largest energies (>30 keV) are found in the solar wind. It is noteworthy that the PHOBOS instruments only covered energies up to a maximum of 25 keV (see Lundin et al., this issue) so that this component, if it were indeed present, could not be detected. It is also important to appreciate that the directional properties of the detectors might in many cases exclude the gyrating particles illustrated in Figure 3. For example, a solar oriented detector with a narrow acceptance angle would only single out particles at the peaks of their cycloidal motion when they had their maximum energies. Thus, a true test of this model must involve similar integrations of the data over solid angle. In particular, the calculation of observed omnidirectional flux spectra is probably more appropriate than imposing narrow angular restrictions on the model since the test particle statistics become poor in the latter case.

One also needs to consider that the test particle distributions are closely controlled by the interplanetary field orientation. The interplanetary field is highly variable in direction so that the patterns in Figure 4 are constantly rotating around the tail axis. Moreover, a significant radial (sunward or antisunward) field component is often present upstream. A radial component not only reduces the maximum pickup ion energies (since the electric field strength is given by the cross product of magnetic field and velocity), but also can displace the trajectories eastward or westward, depending on the draping configuration. Moreover, in the case where a quasi-parallel shock is formed near the subsolar bow shock, much of the dayside magnetosheath field can be turbulent and thereby change the nature of the ion pickup process [cf. Luhmann, et al., 1987]. Thus the direct application of the model described here requires careful selection of orbits with largely transverse, steady interplanetary magnetic fields.

One advantage of this model is that it can be used to estimate the loss rate of planetary ions due to the direct "pickup" process. Although the Nagy and Cravens [1988] oxygen exosphere model has not been experimentally verified, its application here at least provides us with an estimate. Integration of the escaping flux gives a global loss rate of $\sim 10^{23}$ oxygen atoms per second, which is considerably lower than that estimated by Lundin et al. (this issue). However, their values are even much higher than the total ion production rate in the model exosphere above 300 km ($\sim 4 \times 10^{23}$ s^{-1} assuming a production rate of 4×10^{-7} s^{-1}) suggesting that there are either other more important planetary ion scavenging mechanisms or more efficient ionization processes than assumed in the present model, that the Nagy and Cravens [1988] model exosphere underestimates the hot oxygen density, or that the assumptions made in the computation of the observed loss fluxes are too generous. For example, Ip [1988] obtains a factor of ~5 greater exospheric density than Nagy and Cravens, and the ion production processes of electron impact ionization and charge exchange with solar wind protons could add an additional factor of ~4 (totalling 20) to the fluxes in Figures 3 and 4. The answer may lie in first determining whether the gross features of the Martian ion tail (energy spectra, spatial distributions) can be described by this simple model. If there is basic agreement, one can determine whether the observed loss estimates should be revised downward, and, if they cannot, one must raise the question of how and why greater exospheric ion densities than expected are produced. If there is no agreement, or only partial agreement, one needs to consider alternative solar wind-related planetary ion loss mechanisms [e.g., see Brace et al., 1982].

Concluding Remarks

The test particle model presented here is perhaps the simplest "global" physical model that one could construct for the Martian ion wake. It assumes a flow and field model for the underlying solar wind plasma and a specified ion source. Its properties result only from the properties of the background flow and field model and from the spatial distribution of the exosphere model. It is not "self consistent" in that the underlying flow in the magnetosheath is not significantly perturbed by mass loading at all, and the tail, presumed to be caused by the mass loading, is prescribed. However, if the assumed field and flow properties are even approximately accurate, it should provide us with a valid first-order picture of an ion tail of exospheric origin in an induced magnetotail. The presence of a small intrinsic field should make little difference. Only comparisons with the PHOBOS data and with future data from Mars will tell us to what extent this simple description is justified.

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